Strange Electromagnetic and Axial Nucleon Form Factors

A combined analysis of HAPPEx, G^0, and BNL E734 data

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Outline

- Program of parity-violating electron-nucleon elastic scattering experiments will measure the strange vector (electromagnetic) form factors of the nucleon --- but these experiments are insensitive to the strange axial form factor

- Use of neutrino and anti-neutrino elastic scattering data brings in sensitivity to the strange axial form factor as well

- Combination of forward PV data with neutrino and anti-neutrino data allows extraction of vector and axial form factors over a broad Q^2 range

- With better neutrino data, a determination of Δs from the strange axial form factor is possible

Elastic Form Factors in Electroweak Interactions

- Elastic: same initial and final state particles, but with some momentum transfer q between them

- Electroweak: photon-exchange or Z-exchange

The photon exchange (electromagnetic) interaction involves two vector operators, and thus two vector form factors, called F_1 and F_2, appear in the hadronic electromagnetic current:

$$J_\mu^{EM} = {}_N\langle p' | \mathbf{J}_\mu^{EM} | p \rangle_N = \bar{u}(p')\left[\gamma_\mu F_1^{\gamma,N}(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2M}F_2^{\gamma,N}(q^2)\right]u(p)$$

for two nucleon states of momentum p and p'. $\left[q^2 = (p'-p)^2\right]$

Elastic Form Factors in Electroweak Interactions

The Z-exchange (neutral current weak) interaction involves those same vector operators, but since it does not conserve parity it also includes axial-vector and pseudo-scalar operators. So, there are two additional form factors, G_A and G_P, in the hadronic weak current:

$$J_\mu^{NC} = {}_N\langle p' | \mathbf{J}_\mu^{NC} | p \rangle_N = \bar{u}(p')\left[\gamma_\mu F_1^{Z,N}(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2M} F_2^{Z,N}(q^2) \right.$$

$$\left. + \gamma_\mu\gamma_5 G_A^{Z,N}(q^2) + \frac{q_\mu}{M}\gamma_5 G_P^{Z,N}(q^2) \right]u(p)$$

(The pseudo-scalar form factor G_P does not contribute to either PVeN scattering or to neutral-current elastic scattering, so we will ignore it hence.)

A QCD Sum Rule for the Axial Current

The axial current $\gamma_\mu \gamma_5$ is not only the underlying basis of the axial form factor, but is also at the heart of the asymmetric part of the virtual Compton amplitude at work in polarized deep-inelastic scattering. There is a sum rule relating the polarized quark distribution functions $\Delta q(x, Q^2)$ with the corresponding quark contribution to the axial form factor $G_A^q(Q^2)$:

$$\Delta q = G_A^q(Q^2 = 0) = \int_0^1 \Delta q(x, Q^2 = \infty) dx$$

That is, the value of the axial form factor at $Q^2 = 0$ (the "axial charge" Δq) is equal to the integral of the polarized quark distribution function measured at high Q^2.

Therefore a measurement of the strange axial form factor can lead to an understanding of a portion of the nucleon spin puzzle --- a measurement of Δs.

Features of parity-violating forward-scattering *ep* data

• measures linear combination of form factors of interest

• axial terms are doubly suppressed

$\rightarrow (1 - 4\sin^2\theta_W) \sim 0.075$

$\rightarrow$ kinematic factor $\varepsilon' \sim 0$ at forward angles

• significant radiative corrections exist, especially in the axial term

⇒ parity-violating data at forward angles are mostly sensitive to the strange electric and magnetic form factors

Full Expression for the PV *ep* Asymmetry

For a hydrogen target, the asymmetry as a linear combination of G_E^s, G_M^s, G_A^{CC} and G_A^s is :

$$A^p = A_0^p + A_E^p G_E^s + A_M^p G_M^s + A_{AIV}^p G_A^{CC} + A_A^p G_A^s$$

where
$$A_0^p = -K^p \left\{ \begin{array}{c} \left(1 - 4\sin^2\theta_W\right)\left(1 + R_V^p\right)\left(\varepsilon G_E^{p^2} + \tau G_M^{p^2}\right) \\ -\left(1 + R_V^n\right)\left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n\right) \\ -\varepsilon' G_M^p \left(1 - 4\sin^2\theta_W\right)\left[\sqrt{3} R_A^{T=0} G_A^8\right] \end{array} \right\}$$

$$A_E^p = K^p \left\{ \varepsilon G_E^p \left(1 + R_V^0\right) \right\}$$

$$A_M^p = K^p \left\{ \tau G_M^p \left(1 + R_V^0\right) \right\}$$

$$A_{AIV}^p = K^p \left\{ \varepsilon' G_M^p \left(1 - 4\sin^2\theta_W\right)\left(1 + R_A^{T=1}\right) \right\}$$

$$A_A^p = K^p \left\{ \varepsilon' G_M^p \left(1 - 4\sin^2\theta_W\right)\left(1 + R_A^0\right) \right\}$$

$$K^p = \frac{G_F Q^2}{4\pi\sqrt{2}\alpha} \frac{1}{\varepsilon G_E^{p^2} + \tau G_M^{p^2}}$$

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$

$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

Note suppression of axial terms by $(1 - 4\sin^2\theta_W)$ and ε'.

Things known and unknown in the PV *ep* Asymmetry

$G_{E,M}^{p,n}$ = Kelly parametrization $\left[\text{PRC 70 (2004) 068202}\right]$

    with G^0 uncertainties $\left[\text{http}://\text{www.npl.uiuc.edu/exp/G0/Forward}\right]$

$$G_A^{CC} = \frac{g_A}{\left(1 + Q^2/M_A^2\right)^2} \qquad\qquad G_A^8 = \frac{1}{2\sqrt{3}}\frac{\left(3F - D\right)}{\left(1 + Q^2/M_A^2\right)^2}$$

    $M_A = 1.001 \pm 0.020$ GeV $\left[\text{Budd, Bodek and Arrington: hep-ex/0308005 and 0410055}\right]$

    $g_A = 1.2695 \pm 0.0029$ $\left[\text{Particle Data Group 2005}\right]$

    $3F - D = 0.585 \pm 0.025$ $\left[\text{Goto } et\ al.\ \text{PRD 62 (2000) 034017}\right]$

$\left[\text{use of } 3F - D \text{ implies use of flavor-SU(3), but } G_A^8 \text{ is suppressed by } \varepsilon' \text{ and } \left(1 - 4\sin^2\theta_W\right)\right]$

The R's are radiative corrections calculated at $Q^2 = 0$ in the formalism of
Zhu et al. $\left[\text{PRD 62 (2000) 033008}\right]$. The Q^2-dependence is unknown,
and so we have assigned a 100% uncertainty to the values.

    $R_V^p = -0.045$ $R_V^n = -0.012$ $R_V^0 = -0.012$

    $R_A^{T=1} = -0.173$ $R_A^{T=0} = -0.253$ $R_A^0 = -0.552$

    $\left[\text{from evaluation of Arvieux } et\ al.,\ \text{to be published}\right]$

Features of elastic νp data

- measures quadratic combination of form factors of interest

- axial terms are dominant at low Q^2

$$\frac{d\sigma}{dQ^2}\left(\nu p \rightarrow \nu p\right)\xrightarrow[Q^2 \rightarrow 0]{}\frac{G_F^2}{128\pi}\frac{M_p^2}{E_\nu^2}\left[\left(-G_A^u + G_A^d + G_A^s\right)^2 + \left(1 - 4\sin^2\theta_W\right)^2\right]$$

- radiative corrections are insignificant

  [Marciano and Sirlin, PRD 22 (1980) 2695]

⮕ neutrino data are mostly sensitive to the strange axial form factor

Elastic NC neutrino-proton cross sections

$$\frac{d\sigma}{dQ^2}\left(\nu p \to \nu p\right) = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right) \quad \begin{array}{cc} + & \nu \\ \\ - & \bar{\nu} \end{array}$$

$$W = 4\left(E_\nu/M_p - \tau\right) \qquad\qquad \tau = Q^2\big/4M_p^2$$

$$A = \frac{1}{4}\left[\left(G_A^Z\right)^2\left(1+\tau\right) - \left(\left(F_1^Z\right)^2 - \tau\left(F_2^Z\right)^2\right)\left(1-\tau\right) + 4\tau F_1^Z F_2^Z\right]$$

$$B = -\frac{1}{4}G_A^Z\left(F_1^Z + F_2^Z\right)$$

$$C = \frac{1}{64\tau}\left[\left(G_A^Z\right)^2 + \left(F_1^Z\right)^2 + \tau\left(F_2^Z\right)^2\right]$$

Dependence on strange form factors is buried in the weak (Z) form factors.

The BNL E734 Experiment

- performed in mid-1980's

- measured neutrino- and antineutrino-proton elastic scattering

- used wide band neutrino and anti-neutrino beams of $<E_v>=1.25$ GeV

- covered the range $0.45 < Q^2 < 1.05$ GeV^2

- large liquid-scintillator target-detector system

- still the **only** elastic neutrino-proton cross section data available

E734 Results

Uncertainties shown are total (stat and sys).

Correlation coefficient arises from systematic errors.

Q^2 (GeV)^2	$d\sigma/dQ^2(\nu p)$ (fm/GeV)^2	$d\sigma/dQ^2(\bar{\nu}p)$ (fm/GeV)^2	correlation coefficient
0.45	0.165 ± 0.033	0.0756 ± 0.0164	0.134
0.55	0.109 ± 0.017	0.0426 ± 0.0062	0.256
0.65	0.0803 ± 0.0120	0.0283 ± 0.0037	0.294
0.75	0.0657 ± 0.0098	0.0184 ± 0.0027	0.261
0.85	0.0447 ± 0.0092	0.0129 ± 0.0022	0.163
0.95	0.0294 ± 0.0074	0.0108 ± 0.0022	0.116
1.05	0.0205 ± 0.0062	0.0101 ± 0.0027	0.071

Forward-Scattering Parity-Violating *ep* Data

These data must be in the same range of Q^2 as the E734 experiment.

• The original HAPPEx measurement: $Q^2 = 0.477$ GeV^2
[PLB 509 (2001) 211 and PRC 69 (2004) 065501]

• The recent G^0 data covering the range $0.1 < Q^2 < 1.0$ GeV^2
[PRL 95 (2005) 092001]
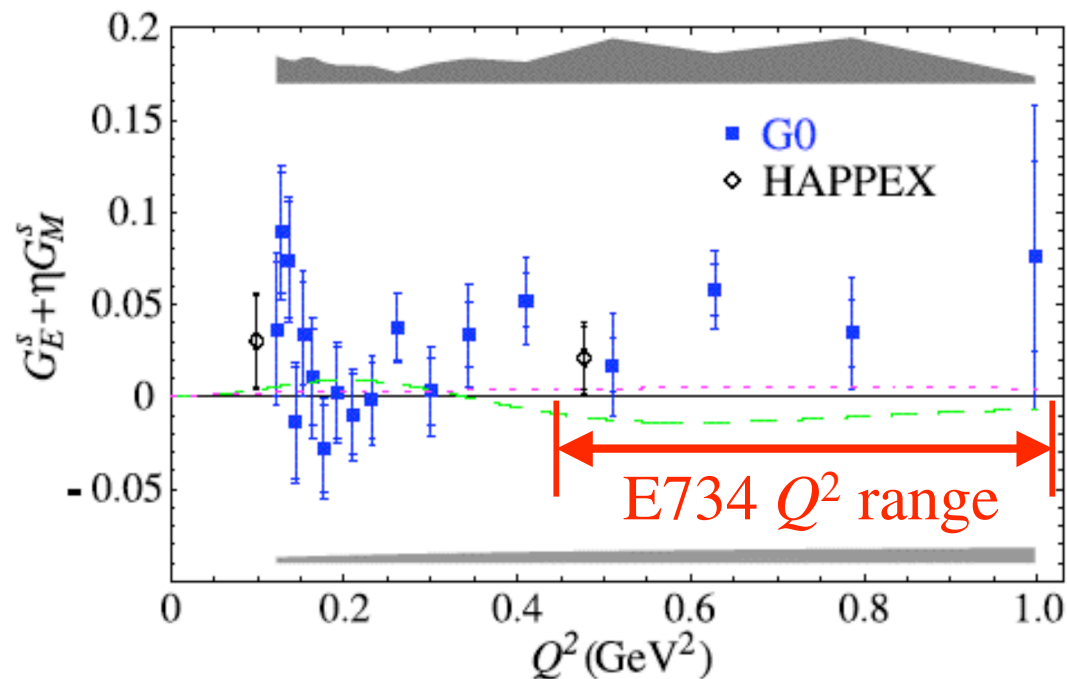
Combination of the *ep* and *vp* data sets

Since the neutrino data are quadratic in the form factors, then there will be in general <u>two solutions</u> when these data sets are combined.

Fortunately, the two solutions are very distinct from each other, and other available data can select the correct physical solution.

# General Features of the two Solutions

|	Solution 1	Solution 2
$G_E{}^s$	Consistent with zero (with large uncertainty)	Large and positive
$G_M{}^s$	Consistent with zero (with large uncertainty)	Large and negative
$G_A{}^s$	Small and negative	Large and positive

There are three strong reasons to prefer **Solution 1**:

- $G_A{}^s$ in Solution 2 is inconsistent with DIS estimates for Δs

- $G_M{}^s$ in Solution 2 is inconsistent with the combined SAMPLE/PVA4/HAPPEx/G0 result of $G_M{}^s = $ ~+0.6 at $Q^2 = 0.1$ GeV^2

- $G_E{}^s$ in Solution 2 is inconsistent with the idea that $G_E{}^s$ should be small, and conflicts with expectation from recent G^0 data that $G_E{}^s$ may be negative near $Q^2 = 0.3$ GeV^2
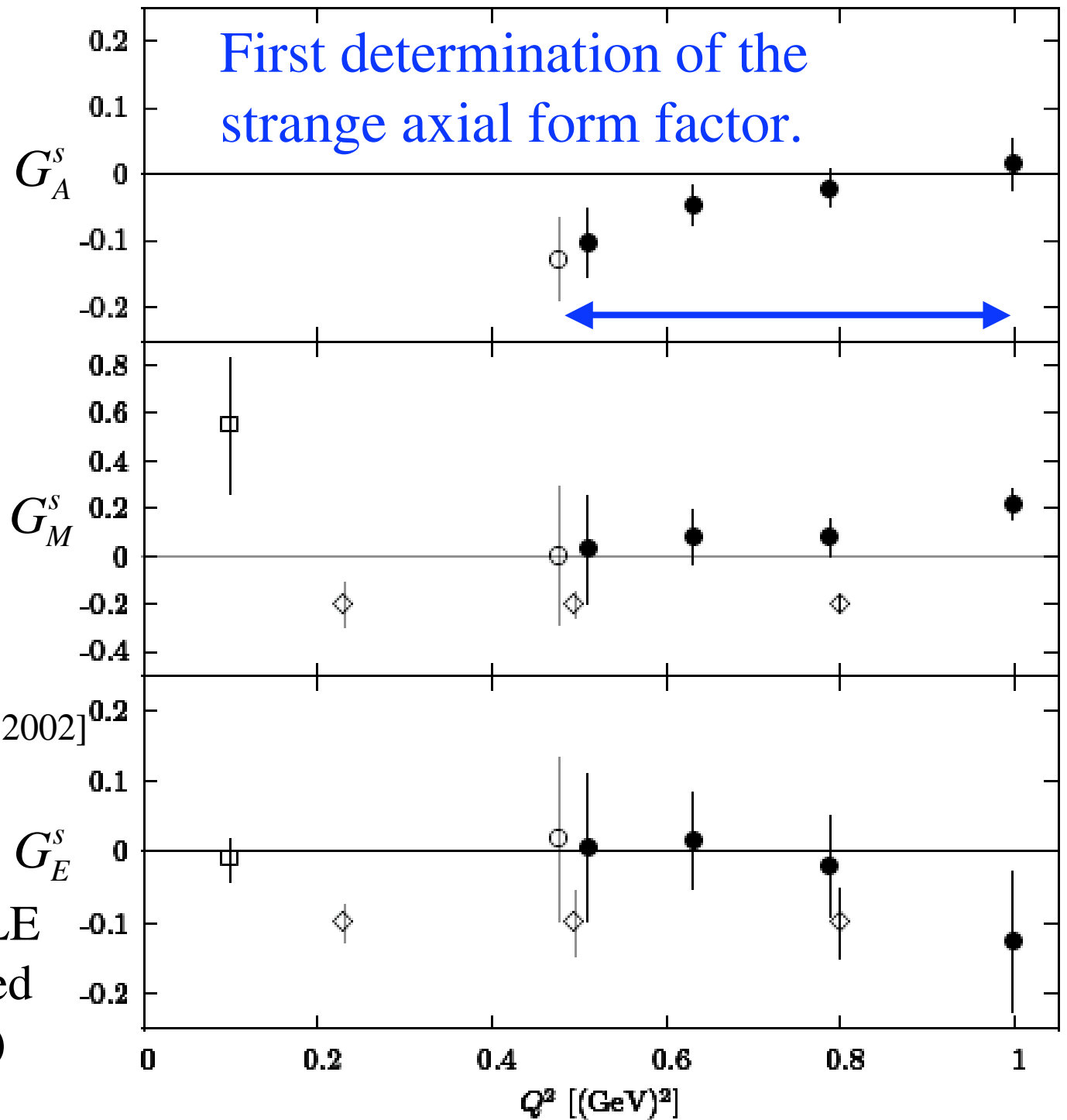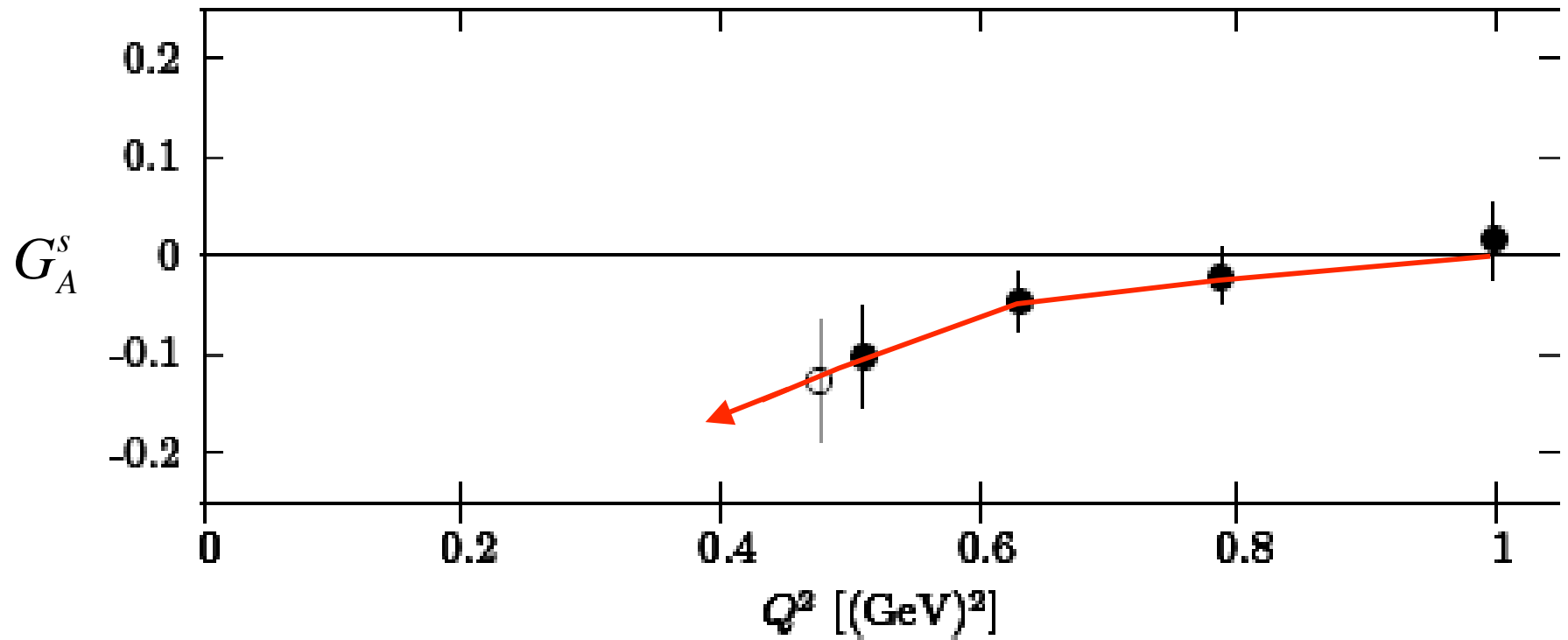
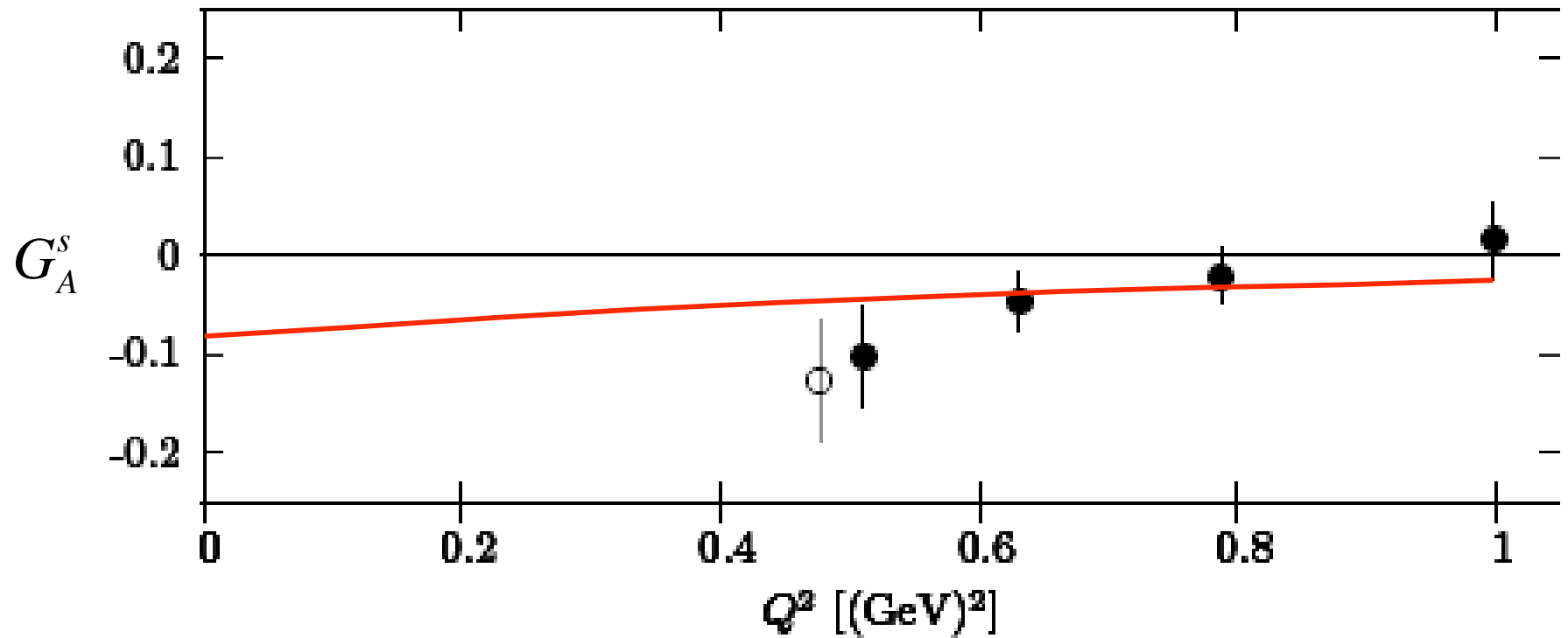I only present Solution 1 in what follows.
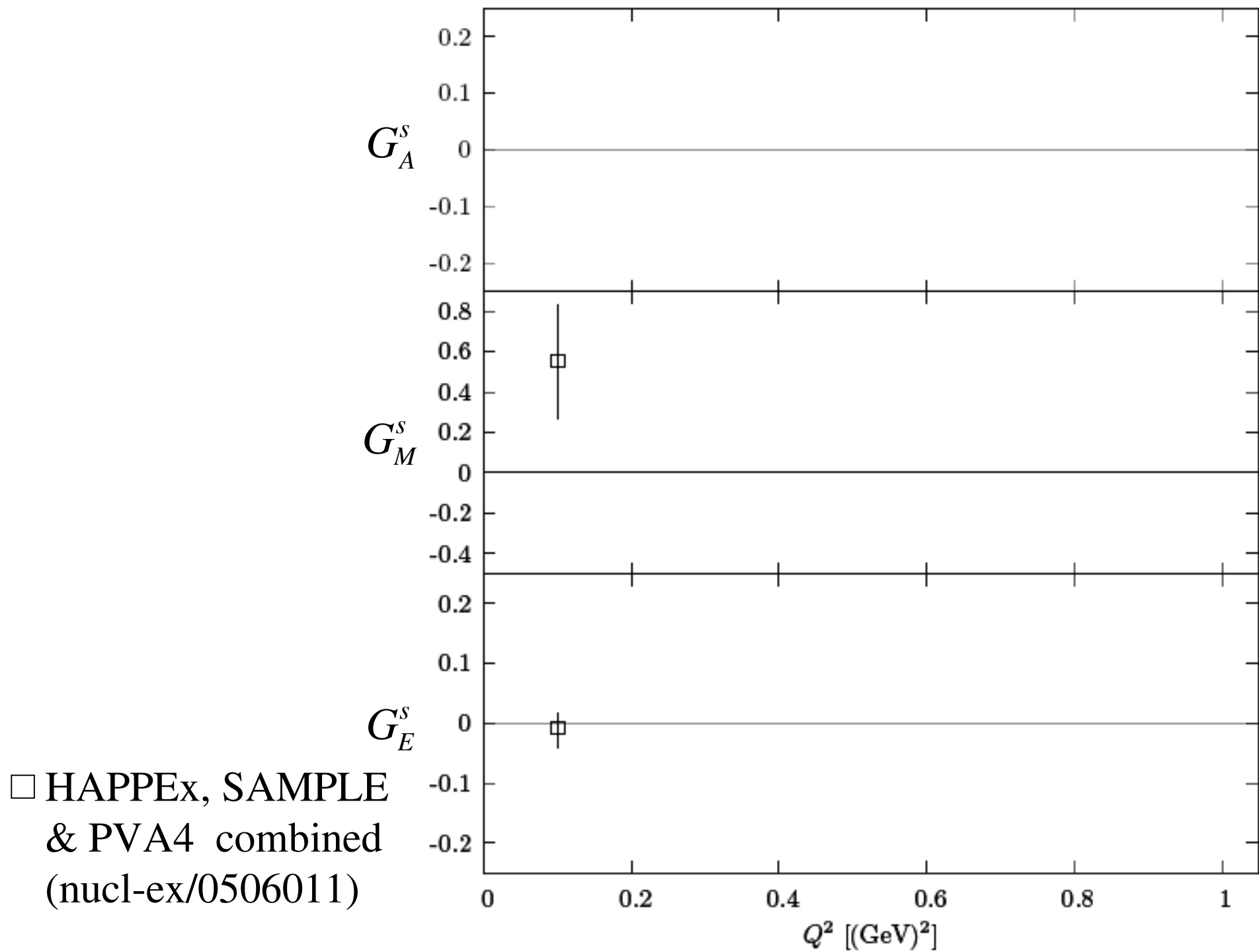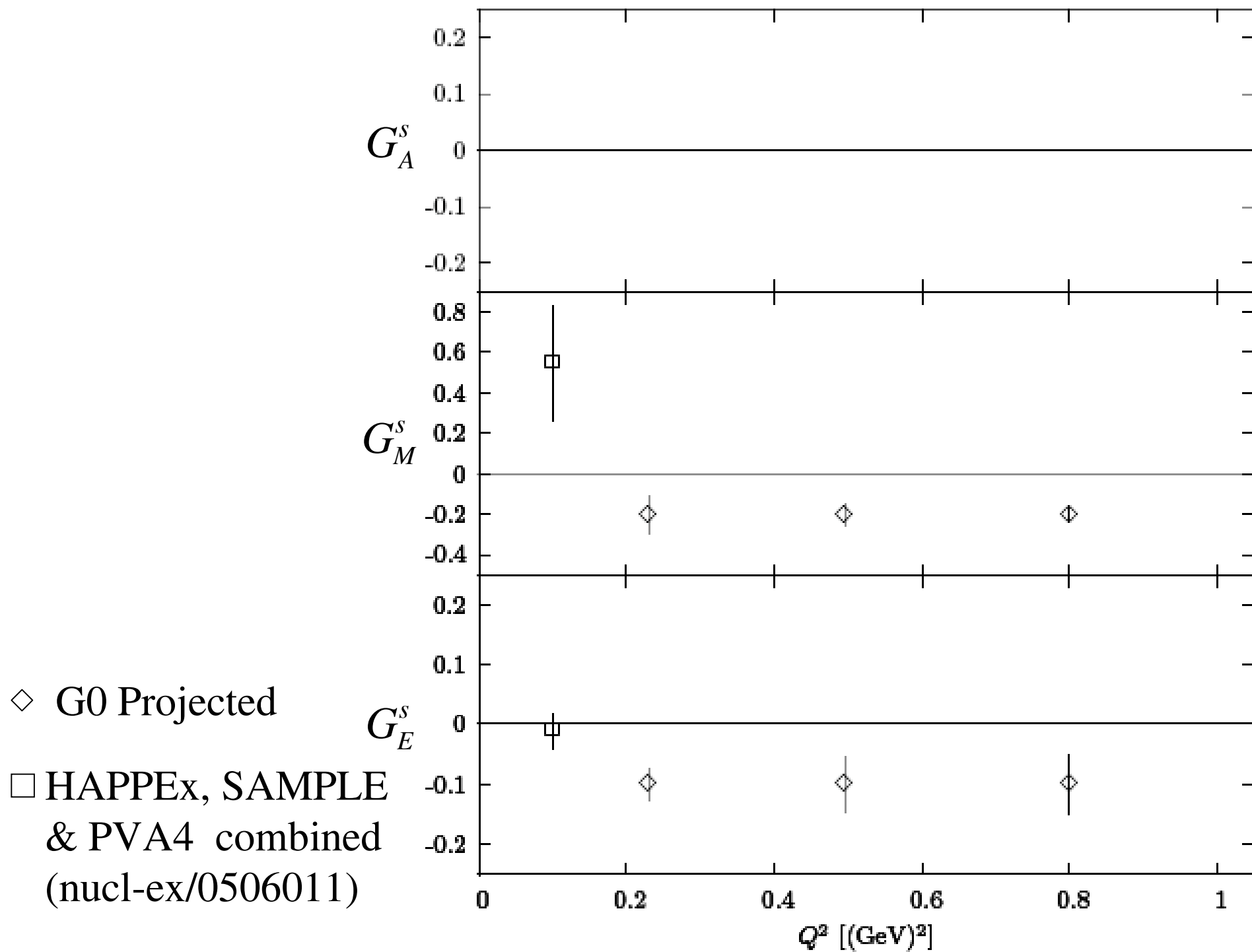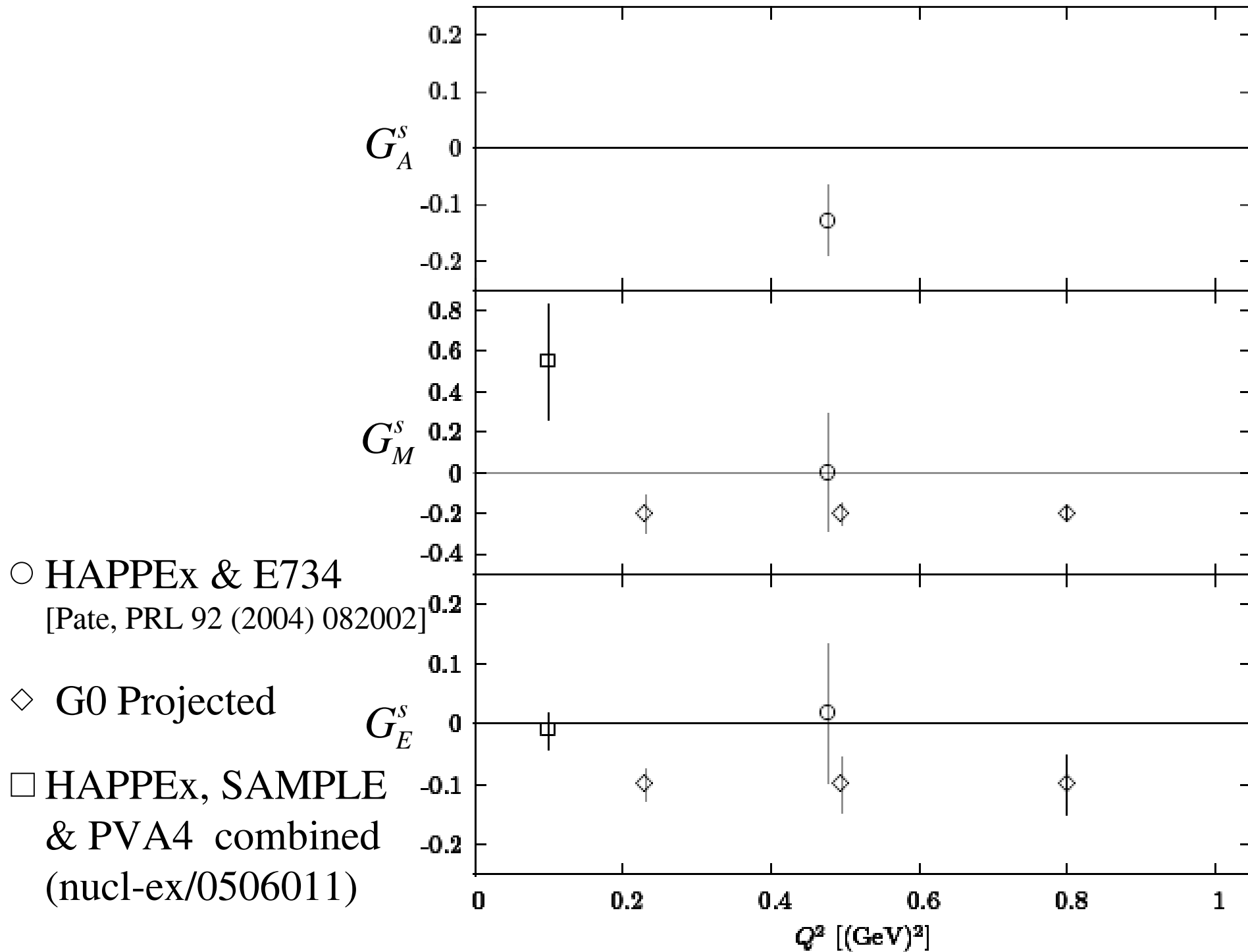
- G0 & E734
  [to be published]

○ HAPPEx & E734
  [Pate, PRL 92 (2004) 082002]

Q^2-dependence suggests $\Delta s < 0$!

- G0 & E734
  [to be published]

○ HAPPEx & E734
  [Pate, PRL 92 (2004) 082002]

Recent calculation by Silva, Kim, Urbano, and Goeke (hep-ph/0509281) based on chiral quark-soliton model is in rough agreement with the data.

A future experiment to determine the three strange form factors and Δs

The program I have described determines the strange axial form factor down to $Q^2 = 0.45$ GeV^2 successfully, but it does not determine the Q^2-dependence sufficiently for an extrapolation down to $Q^2 = 0$.

A better neutrino experiment is needed, with a focus on determining these form factors. The large uncertainties in the E734 data limit their usefulness beyond what I have shown here.

A new experiment has been proposed to measure elastic and quasi-elastic neutrino-nucleon scattering to sufficiently low Q^2 to measure Δs directly.

FINeSSE* Determination of Δs

Measure ratio of NC to CC neutrino scattering from nucleons:

$$R_{\text{NC/CC}} = \frac{\sigma\left(\nu p \to \nu p\right)}{\sigma\left(\nu n \to \mu^- p\right)}$$

$\Rightarrow$ Numerator is sensitive to $\left(-G_A^{CC} + \boxed{G_A^s}\right)$

$\Rightarrow$ Denominator is sensitive to G_A^{CC} only

$\Rightarrow$ Both processes have unique charged particle
    final state signatures

$\Rightarrow$ Ratio largely eliminates uncertainties in neutrino flux,
    detector efficiency, and (we expect) nuclear target effects

* B. Fleming (Yale) and R. Tayloe (Indiana), spokespersons

FINeSSE Determination of Δs

If the ratio of NC to CC processes is measured

for <u>both</u> neutrino and anti - ncutrino scattering

$$R_{\text{NC/CC}} = \frac{\sigma(\nu p \rightarrow \nu p)}{\sigma(\nu n \rightarrow \mu^- p)} \qquad \overline{R}_{\text{NC/CC}} = \frac{\sigma(\overline{\nu}p \rightarrow \overline{\nu}p)}{\sigma(\overline{\nu}p \rightarrow \mu^+ n)}$$

and combined with forward PV $\vec{e}p$ scattering data,

the uncertainty in the strange axial form factor can be pushed

down to ± 0.02.

However, these uncertainty estimates do not include any
contributions from nuclear initial state and final state effects.
The calculation and understanding of these effects is a
critical component of the FINeSSE physics program.

Theoretical Effort Related to FINeSSE

- Meucci, Giusti, and Pacati at INFN-Pavia [1]

- van der Ventel and Piekarewicz [2,3]

- Maieron, Martinez, Caballero, and Udias [4,5]

- Martinez, Lava, Jachowicz, Ryckebusch, Vantournhout, and Udias [6]

These groups generally employ a relativistic PWIA for the baseline calculation, and use a variety of models to explore initial and final state nuclear effects (relativistic optical model or relativistic Glauber approximation, for example).

Preliminary indication from [6] is that nuclear effects cancel very nicely in the ratios to be measured in FINeSSE.

[1] Nucl. Phys. A 744 (2004) 307.

[2] Phys. Rev. C 69 (2004) 035501

[3] nucl-th/0506071, submitted to Phys. Rev. C

[4] Phys. Rev. C 68 (2003) 048501

[5] Nucl. Phys. Proc. Suppl. 139 (2005) 226

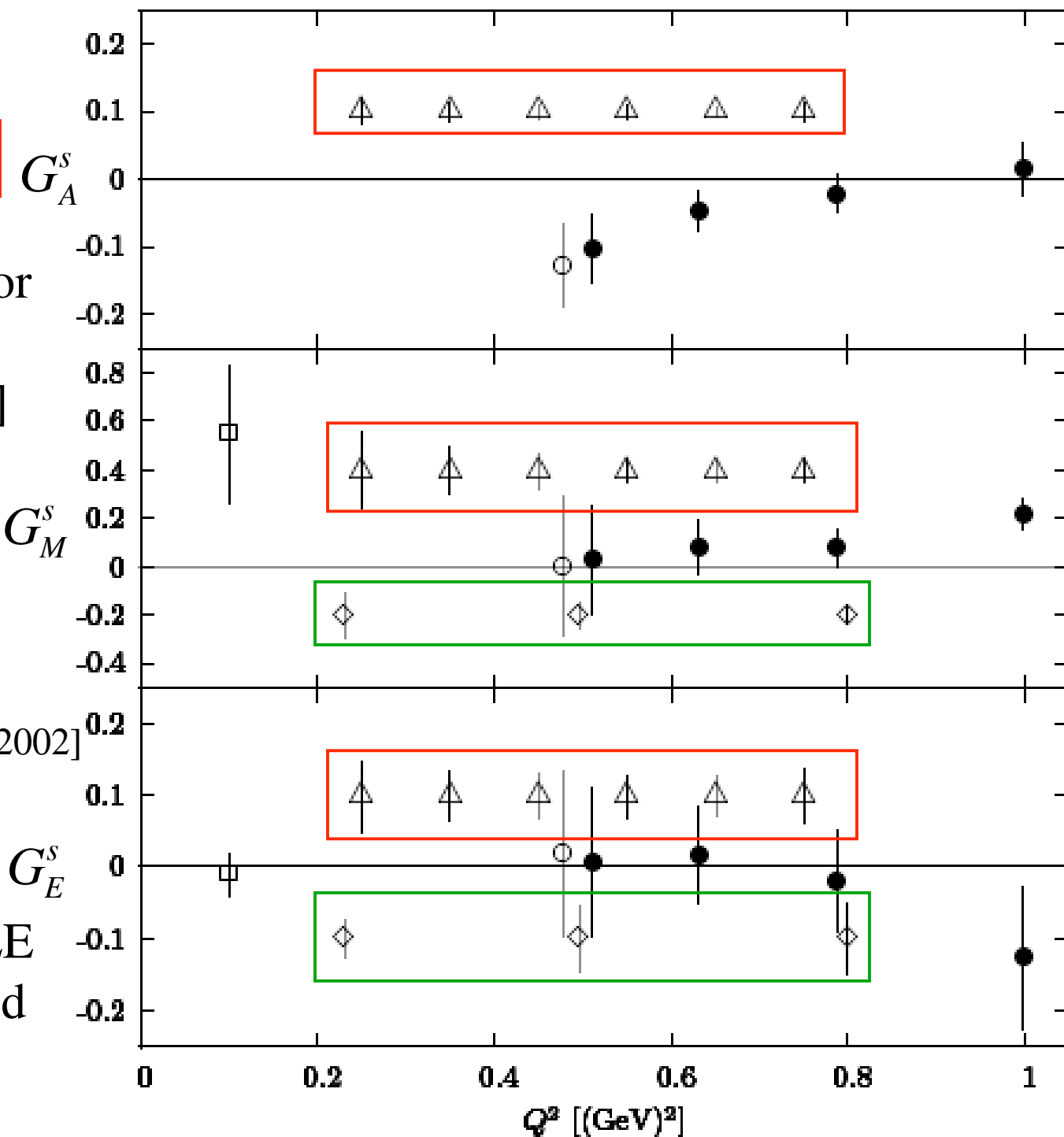[6] nucl-th/0505008, submitted to Phys. Rev. C

△ FINeSSE (& G0)
[exp. proposal:
no nuclear initial or
final state effects
included in errors]

● G0 & E734
[to be published]

○ HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

◇ G0 Projected

□ HAPPEx, SAMPLE
& PVA4 combined
(nucl-ex/0506011)

In conclusion…

Recent data from parity-violating electron-nucleon scattering experiments has brought the discovery of the strange vector form factors from the future into the present. Additional data from these experiments in the next few years will add to this new information about the strangeness component of the nucleon.

However, an even richer array of results, including also the strange axial form factor and the determination of Δs, can be produced if we can bring neutrino-proton scattering data into the analysis.

The E734 data have insufficient precision and too narrow a Q^2 range to achieve the full potential of this physics program. The FINeSSE project can provide the necessary data to make this physics program a success.